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Governing science as a complex adaptive system

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Abstract

Research policy is a complex matter. Copying best practices in research policy, as identified by benchmarking studies, is popular amongst policy makers but fails because of 'knowledge asymmetries'. Research fields exhibit distinct knowledge dynamics that respond differently to governance interventions. Extending the idea of search regimes, this paper aims at providing a policy model for different knowledge dynamics by elaborating the notion of knowledge production as a complex adaptive system.

Complex regimes emerge from three interacting sources of variance. In our conceptualisation, researchers are the nodes that carry the science system. Research can be considered as geographically situated practices with site specific skills, equipments and tools. The emergent science level refers to the formal communication activities of the knowledge published in journals and books, and announced in conferences. The contextual dynamics refer to the ways in which knowledge production provides resources for social and economic development.

This conceptualization allows us to disaggregate knowledge dynamics both in horizontal (field related) and vertical (level related) dimensions by articulating the three different dynamics and their path dependencies (in research, science and society) in co-evolution with each other to produce distinct search regimes in each field. The implication for research governance is that generic measures can sometimes be helpful but there is clear need for disaggregated measures targeting field specific search regimes. Governing knowledge production through disaggregated measures means targeting in a distinct way not only different fields, but also, and more importantly, the interactions between local research practices, emergent scientific landscapes, and the field's relationship to its societal context. If all three "levels" are aligned, there is a stable regime.

Keywords: search regime, research and innovation governance, complex adaptive system

1. Introduction

Research policy is a complex matter. Copying best practices in research policy, as identified by benchmarking studies, is popular amongst policy makers but fails because of 'knowledge asymmetries' (Asheim, Boschma et al. 2006; Bonaccorsi 2007). Research fields exhibit distinct and localised knowledge dynamics that respond differently to governance interventions. This paper is concerned with these inter-science differences in the properties of 'search regimes' and the nature of the dynamics that underlie such properties. It presents a research policy model, based on the idea of knowledge production as a complex adaptive system. Extending earlier conceptualisations of 'search regimes' (Bonaccorsi 2007), this policy model brings together three different dynamics (research, science and society) in co-evolution with each other to produce distinct search regimes in each field. There are urgent challenges in research and innovation policy that make it necessary to rethink existing policy interventions. These challenges include the increasingly diverse practices of knowledge production, the increasing globalisation of science and innovation and the increased socio-economic use of knowledge in society. On different levels of analysis, these challenges all relate to more heterogeneity in the sciences.

Conceptualisations of inter-science differences and dynamics are thus increasingly important. However, existing models of science insufficiently address the different levels of analysis of knowledge dynamics. Following Simon (1973), we argue that in addition to horizontal disaggregation, we need to take into account vertical disaggregation of knowledge dynamics to understand the dynamics of search regimes. Horizontal disaggregation refers to distinguishing between different fields, and vertical disaggregation refers to different levels of interaction and communication with respect to knowledge. For this purpose, the emergent dynamics of fields are discussed, connecting micro level actions with emergent macro phenomena and contextual dynamics. If knowledge production is seen as a complex evolving system, co-evolving within a societal environment, then our thinking about research governance changes. The complex adaptive systems approach shifts the perspective on governance from top down steering to optimizing the productivity of science by taking into account the specific local conditions, the global body of knowledge and the societal interactions.

The focus of this paper is scientific knowledge as opposed to technological knowledge or other knowledge inputs to innovation processes. Here, 'scientific' is defined quite broadly (in the Continental European rather than the Anglo-Saxon sense) to include not only the natural sciences and engineering but also the social sciences and humanities. Secondly, the primary focus is on the public scientific system, as opposed to the private or corporate scientific system. The paper is divided into five sections. Section two explores the current challenges in research policy, followed by a discussing of existing taxonomic exercises to distinguish patterns of knowledge dynamics in section three. Section four suggests a new conceptualisation of search regimes, drawn from empirical evidence and the notion of knowledge production as a complex adaptive system Section five explores the implications of this conceptualisation of search regimes for research governance. Section six is the conclusion.

2. Challenges in research policy

Major challenges in research and innovation make it necessary to rethink our policy models for research governance. The first challenges relates to the increased heterogeneity in knowledge production. The use of ICTs has provided increasing variation in researching practices by enabling additional models, maps and tools to be generated: simulated experimentation *in silico*, algorithms for pattern identification in biomedicine, visualization tools, modelling and simulations have allowed not only new methods of analysis, but also new types of output to be generated (Heimeriks and Vasileiadou 2008). Furthermore, additional topics of research are emerging. Not only natural phenomena in the real world, but also the properties and behaviour of artefacts (such as computers, models and information) have become in important focus of research. Furthermore, the availability of data and computer power has made it possible that new types of research questions can be pursued related to complex processes and network dynamics. Additionally, ICTs influence the social organization of research, by falicilitating collaboration between researchers thus resulting in increasing numbers of authors per publication, increased numbers of publications with international co-authors, and the allocation of research money for ever larger groups of researchers.

The variety of modes of collaboration, concepts and tools creates a heterogeneity that is (partially) adopted in ways that reflect different field-specific patterns and needs. This increased heterogeneity in research practices imposes new challenges for research governance. The “one size fits all” approach to research governance becomes increasingly counterproductive.

The second major challenge is related to the globalisation of the sciences. More and more countries contribute to the global body of knowledge (Wagner 2008). But, an apparent paradox in research governance is that scientific knowledge is considered to be universally accessible, while funded on a local and national basis (Wagner 2008). As a consequence of globalisation, there has been a growing emphasis on science and innovation in industrialised countries as a response to the increasing competition from emerging economies. As a result, competition in science and innovation has become ever fiercer as more researchers join in. The increasing competition and the growing costs of research have also contributed to a concentration of research resources and the emergence of a more pronounced hierarchy of “creative capitals” (Florida 2002) and research universities. In other words, knowledge production in each field is not evenly distributed around the globe, but takes place in specific locations, different ones for each field of knowledge production. Knowledge and R&D are valuable resources that have a high impact on national economies, but governments often fail to design policy measures that fit local conditions (Foray 2006).

The third challenge concerns the changing interface of science and society with the move towards a more knowledge-intensive society or the ‘knowledge economy’ (e.g. Cowan, David et al. 2000). An important aspect of this development is that innovation is coming to depend increasingly on science and technology. On the one hand, research is assumed to be an autonomous set of activities that just have to be left on their own to develop most fruitfully. On the other hand, increasing demands are made on science to solve societal problems and contribute to economic growth. The importance of research governance in this respect has increased in recent years as a result of the emergence of the knowledge society. However, the types of valorization of knowledge differs widely between fields; different fields contribute to knowledge resources in a wide variety of social, economical, political and innovative processes (Webster 2006).

3. Disaggregating knowledge dynamics; search regimes

In order to address these research policy challenges, there is clear need for disaggregating knowledge dynamics into their distinct and localised characteristics. The scientific landscape consists of a large number of relatively weakly linked research fields (Van den Besselaar and Heimeriks 2001; Heimeriks 2005). These disciplines and field differ from each other in many respects. The differences encompass both intellectual and social characteristics (Whitley 2000). Furthermore, disciplines and fields are subject to dynamics and change. These differences and dynamics are relevant for research management and governance. Bonaccorsi points out that general comparison between European and American knowledge production fails to recognise the fact that European science has different characteristics than American science (Bonaccorsi 2007). European science tends to be strong in fields characterized by slow growth and stable search regimes. European science is also strong in fields characterized by large infrastructures, while it is much less prepared in fields characterized by human capital and institutional complementarities.

Horizontal disaggregation of science its different fields is necessary to understand and act upon the different knowledge dynamics. Several conceptualisations have been proposed for this purpose. These include the analysis in terms of the ‘Mode 1’ and ‘Mode 2’ versions of the knowledge production process, the notion of ‘Pasteur’s Quadrant’ research, and shifts in ‘search regimes’. Additionally, the seminal work of Whitley will be included in this list, although its impact on research governance has been limited. These conceptualisations of inter-science differences and dynamics are important because they identify common properties in distinct sets of knowledge production activities. Such properties contribute to interpreting asymmetries in the dynamics of knowledge and may guide research policy efforts. In this section, we critically analyse each of these conceptualisations in turn.

In the post-war period, much discussion of research policy was guided by the distinction between ‘basic research’ and ‘applied research’ (Martin 2010). However, Stokes argued that one needed to replace this basic/applied dichotomy with a two-by-two matrix (Stokes 1997). Besides research aiming to generate new understanding but not to develop a new application (Bohr’s Quadrant), and research aiming to develop a new application but not new understanding (Edison’s Quadrant), one can also have research aiming *both* to produce new understanding *and* to develop a new application and thus meet some economic or societal need (Pasteur’s Quadrant).

There are two main problems with Pasteur’s Quadrant (Martin 2010). First, it is a useful descriptive taxonomy rather than an analytical model. Secondly, the great majority of research conducted in universities and public research laboratories falls in Pasteur’s Quadrant (especially if one adopts a long-term view) rather than Bohr’s Quadrant. Scientists in even the most ‘basic’ of sciences tend to argue that ultimately society will benefit in some (yet to be defined) way from the results of their work.

The most influential diagnosis that has been proposed to describe the changing knowledge dynamics is the transition from Mode 1 to Mode 2 science. According to Gibbons et al. (1994), we witness a shift from disciplinary, university-based type of science, to one which is multidisciplinary, based on networks of distributed knowledge, and oriented towards problem solving and societal challenges. One of the difficulties of this diagnosis is that it emphasizes changes that take place outside science, that is, in the institutional, political, financial and social environment surrounding science. Furthermore, its claims appear to be based more on assertion than evidence. Empirical studies show that in fact there is a wide variety of heterogeneous developments taking place in knowledge production that are not accurately captured by the Mode 2 diagnosis (Heimeriks et al, 2008, Hessels et al, 2008). Additionally, the claim that we are moving towards a *new* mode of knowledge production is historically suspect. Mode 2 knowledge production is certainly not new, from the time of the emergence of modern science, there has always been ‘research in the context of application’

Bonaccorsi's search regimes aim at providing a summary description of a consistent set of dynamic properties of the specific research processes in a field (Bonaccorsi 2008). Three dimensions capture the essence of relevant distinctions: the rate of growth, the degree of divergence and the level of complementarity. By combining these three dimensions one is able to characterize several search regimes.

The question of growth of scientific knowledge is central in this conceptualisation of science, and according to Bonaccorsi, the direction of growth (converging or diverging) is a defining attribute of a field. The direction of growth can distinguish between convergent and divergent search regimes. By convergent search regime Bonaccorsi refers to a dynamic pattern in which given one or more common premises (e.g. an accepted theory and an agreed research question or general hypothesis) each conclusion (i.e. experimental evidence or theoretical advancement) is a premise for further conclusions. In addition, all intermediate conclusions adds support to a general conclusion. By divergent search regime is meant a dynamic pattern in which given one or more common premises each conclusion gives origin to many other sub-hypotheses and then research programmes. A third relevant dimension to characterize a search regime is the level of complementarity; the extent to which different human or material resources are needed, in addition to the intellectual resources. The simplest form of complementarity depends on the existence of a minimum collection of resources needed to perform the research activity. The idea of a search regime provides a useful entrance point for exploring the hypothesis that there are simultaneously different knowledge dynamics at work that require different institutional settings and policy arrangements.

Nevertheless, there are a number of questions with the Bonaccorsi framework that need to be addressed. First, while it provides a static snapshot the state of a field, it uses dynamic elements like growth and divergence. And what constitutes a stable regime? How does a scientific field switch from one category to another? And what might bring about such a change? Furthermore, how much further forward does the Bonaccorsi framework take us compared with Kuhn's analysis in terms of 'pre-paradigmatic science', 'revolutionary science', and 'normal science'(Kuhn 1962; Kuhn 1970)?

From a different perspective, Whitley argues that the major differences between disciplines (and fields) can be characterized in terms of two interrelated concepts: the degree of mutual dependence between researchers or fields in making competent and significant contributions to a body of knowledge and the degree of task uncertainty in producing contributions and evaluating knowledge claims (Whitley 2000). 'Mutual dependence' refers to the degree to which scientists in a field depend on their colleagues for reputation and access to resources, as well as on their results, ideas and procedures as contributions to collective intellectual goals. When mutual dependence in a field is high, there tends to be a high degree of collective identity, competition between researchers is also higher, the degree of local and individual autonomy from collective goals and standards is low, and the communication system in the field is formalised.

'Task uncertainty' refers to the degree of uncertainty in terms of work techniques, intellectual priorities, and research topics in different scientific fields, and it results from the innovative character that scientific outcomes need to have. When task uncertainty in a field is high, research strategies and procedures are less standardised, and the results are less easily compared and coordinated. In those fields, centralised control over research strategies and performance standards is less feasible, and the overall coordination and integration of research is reduced (pp. 130-131).

Both Whitley and Bonaccorsi focus on the field differences that may guide governance models of research. However, just focusing on horizontal disaggregation does not allow for accurate policy intervention. It is important to take into account these different levels of analysis because the dynamics used to characterise search regimes relate to different processes on different levels of analysis. For example, a field may be characterised by a strong and stable disciplinary identity in terms of publication patterns, while a diverging variety of skills and tools is used in research practices (e.g. genetics).

Similarly, Whitley's analysis fails to distinguish between the local, global and contextual dynamics of sciences: Can we understand mutual dependency as dependence between texts, institutions or researchers? Is dependence on a variety of audiences related to the dependence of researchers on common infrastructure? Mutual dependency and task uncertainty represent different aspects on different levels of analysis. On the research level, these concepts can be associated with the existing variety in tools, the use of infrastructures as well as with the intellectual division of labour. On the science level however, these concepts relate to the level of disciplinarity (e.g., the intellectual coherence and the extent to which this is reproduced in time) while from a societal perspective, the co-production of knowledge with societal actors and the variety of (non-academic) audiences are defining features.

The policy challenges discussed in the previous section (diverse practices of knowledge production, the increasing globalisation of science and innovation and the increased socio-economic use of knowledge in society) signal the importance of different levels of analysis to be addressed. In short, in addition to horizontal (field) differences, also different levels of analysis need to be taken into account when designing instruments for policy intervention. Following Simon (1973), we argue that the dynamics of systems can only be understood by taking into account both the vertical separation (hierarchical levels of analysis) and the horizontal separation of subsystems at the same hierarchic level (Simon 1973). 'Horizontal coupling of the components of a system has great importance for evolutionary just as the vertical coupling does' (Simon 1973, pp16). The combination of horizontal and vertical disaggregated patterns suggested here, aims at overcoming these limitations of existing conceptualisations of search regimes.

4. CAS: Complex adaptive systems

The starting point of the conceptualization presented here, is the notion of a complex adaptive system (CAS). There is at present no generally agreed definition of what counts as a CAS. However, existing literature suggests several traits that are commonly accepted and that serve as building blocks for our conceptual operationalisation of science as a complex system (Simon 1973; Mitleton-Kelly 2003; Mitleton-Kelly 2006).

First, CAS consists of agents (e.g., cells, species, social actors, researchers and firms) assumed to follow certain behavioural schemata, which are characterized by heterogeneity. Second, as no central control directs the behaviour of agents, self-organization occurs when agents are acting on locally available information about the behaviour of other agents. These local processes give rise to system behaviour with limited predictability (often denoted emergent properties) associated with CAS (e.g. (Holland and Miller 1991). Third, systems are capable of co-evolution because of their interconnectedness (Duit and Galaz 2008). The point is that interconnected systems contain interactions driven by both positive and negative feedback and processes operating over a range of spatial and temporal scales. Connectivity applies not only to elements within a system but also to related systems within an environment (Kauffman 1993). The way each element influences and is in turn influenced by all other related elements in a system is part of the process of co-evolution. Complexity also emphasises co-evolution with rather than adaptation to a changing environment and thus changes the perspective and the assumptions, which underlie traditional policy interventions. Finally, the future of a complex system is dependent on its past. More generally, systems (and their agents) exhibit path dependency. Path dependence refers to the limitations provided by previous developments of a system, even though past circumstances may no longer be relevant. That past may be stored or memorized, at both the microscopic and macroscopic levels, at the level of the individual or the level of the whole that emerges from the interaction of these individuals.

Knowledge production as CAS

These traits of complex adaptive systems may well be applied to science. Science is a complex because millions of researchers around the world interact in both competitive and collaborative ways, with no overall direction. Science is adaptive and co-evolving because both the science system and its constituent researchers respond to changing environmental conditions such as shifts in research priorities of granting organisations or new discoveries. Science is recognisably a system, a collection of individuals and institutions contributing to a common body of knowledge. And it is open; scientists can cross from field to field and investigate new areas (Wagner 2008).

Following Krohn and Küppers, we suggest that science refers to an emergent system of organized and systematic knowledge, whereas research are the basic practices of human actors in this system (Krohn and Küppers 1989). In line with this view, we can understand the sciences as complex adaptive systems operating at three interrelated but analytically distinct levels[1] (Rip 1990; Heimeriks and Vasileiadou 2008). The research level consists of the everyday activities of researchers in their local context of work, the science level refers to the emergent body of knowledge and societal dynamics provide the environment in which this science system functions. In the following sections we elaborate the dynamic processes in research, science and society that all provide distinct path dependencies in the evolution organizations and institutions.

Research in CAS

Researchers are the nodes that carry the science systems. At the research level, the interactions entail working together in formulation of the research design, data gathering, data analysis, production of results, and/or writing up of reports, and can be understood as "solving problems together"[2]. Research is a locally situated practice with site specific skills, equipments and tools, geographically localised at a site of investigation: a laboratory, plant or field site (Rouse 1991). Both what constitutes a research opportunity and how it is dealt with are locally situated. At this research level, researchers compete and collaborate. Collaboration has several functions (Vasileiadou 2009). The first is as a socialization mechanism, which relates to the exchange of tacit knowledge. The second function of collaboration relates to its role as a quality-control mechanism. The third function of collaboration is to bridge different expertise and skills together. With the growing specialisation in science and the progressive professionalization (Cronin, Snyder et al. 1998), it is becoming increasingly difficult for a researcher to possess the necessary skills and knowledge to solve problems alone. The highly durable capital assets and the information channels and codes required by multiperson organizations to function efficiently , provide path dependent constraints in the evolution of local institutions (David 1994). Especially established sciences make use of large physical infrastructures, with high energy physics as its most extreme example.

Science in CAS

The second level is the emergent science level, which refers to the formal communication activities of scientists, that is, the end products published in journals and books, and announced in conferences. The novelty of the results that are communicated ensures the reputation of the individual scientist and his or her niche in the field. The dissemination of results through communication media translates the 'research output' into a 'body of knowledge' where claims are utilized (accepted, criticized, rejected) by other scientists. The collective coordination of outcomes takes place mainly through the dissemination of the results, which is generally based on a peer-review system, whether the means of dissemination are scientific journals or monographs and books. This collective and evolving body of knowledge can be seen as the systemic science level.

The focus on the emergent communication system enables a shift away from the social process of construction by researchers to the emergent constructions as knowledge based (Lucio-Arias and Leydesdorff 2009). At this level, knowledge production is a collective and

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[1] Of course, all processes are necessarily interlinked and the boundaries between the researchers and its 'environment' are not clear-cut and stable. Hence the notion of a complex co-evolving knowledge production system is one of intricate and multiple intertwined interactions and relationships.

[2] Krohn and Küppers (1989) stress the importance of research groups as 'Research producing unit' (rpu). However, research groups are themselves a heterogeneous category with enormous differences in size, levels of aggregation and interaction patterns. Precisely these differences we aim to explain by the vertical and horizontal disaggregation proposed in this paper. For example, (Vasileiadou 2009) argues that research groups themselves are emergent phenomena.

distributed activity in which the existing results in a field are related to new findings (Fujigaki and Leydesdorff 2000). The formal communications in scientific journals result in the emergence of a system with a stable, accumulative and consistent development of knowledge production (Leydesdorff 2001).

Path dependency in science is provided by the disciplinary landscape carried by various media, but mainly by the scholarly journal. The sequence of knowledge claims, by emphasizing the differences with previous claims, constitutes the research front of a field, and brings the field further. At the same time, it can lead to a relatively stable definition of the field, in as far as the knowledge claims remain referring to a stable literature, which constitutes the intellectual foundation of the field. When a field is stabilized in this way, the process of circular causality leads to further stabilization: the new researchers are inclined to position themselves in terms of the intellectual base, and in terms of the research front, and therefore a constant referring to the same literature takes place, and that reinforces the stability of the field.

Society in CAS

The third level is provided by the societal environment in which the science system evolves. Science is an open system that is coupled to other parts of society; it is neither internally, nor externally determined, its development is caused by a complex interplay of internal and external factors, it is a relatively autonomous system. However, in recent years additional emphasis has been put on the socio-economic value of scientific knowledge in society.

In general, a system relies on its environment for resources. In this context, scientific communities act in political forums, lobby for their interests, and pursue their interests and links alongside and vis-à-vis social, political and economic actors. In other words this level relates to all interactions of researchers outside their scientific community and the non-academic use of knowledge as resource for social and technological developments. In this context, processes such as popularization of science, valorisation of research and formulating policy advice are relevant.

The societal environment plays an increasing role in providing path dependent constraints to knowledge production (Ziman 1994.). Knowledge is becoming the crucial resource of social and economic development, and policymakers are guided in their funding choices by persistent economic and societal developments, as well as shaping the comparative advantage of the developed countries (Romer 1994). There is a widespread discussion on a new ‘social contract’ between science and society (Nowotny, Scott et al. 2001). It is focusing on the co-evolutionary way knowledge, technology and society are developing and engaged in the implications of the new form of knowledge production. According to Nowotny et al., knowledge production takes its economic, political, social and cultural context early into consideration (reflexivity) and gets socially more robust (contextualisation).

Interacting levels

Interactions between the local research practices, scientific fields and society are multidirectional and involve positive and negative feedback loops. In other words, research, science and society interact and shape each other in a process of co-evolution (Whitley 2000; Rip 2002). Co-evolution affects both individual researchers and science systems and is operational at different levels, scales or domains.[3]

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[3] As Eve Mitleton-Kelly (2003) points out that it is difficult to find the precise term which differentiates the different entities without importing notions of hierarchy.

A scientific field ('body of knowledge') constrains the set of trajectories that a researcher may explore, as well as the range of available strategies, competencies and forms of organisation. But the degree of diversity among researchers within a field relates in different ways to the 'strength' of a scientific regime upon the discretionary behaviour of individual researchers. Science relates to research activities insofar as the science level creates resources for individual researchers, such as recognition and reputation, which feed back into their research practices in time. As mentioned, knowledge production should be seen in the context of each local organisation's unique trajectory and as a process of accumulation of associated specific capabilities, distinctive competences and infrastructures. Thus science activities can also be seen as distinct ways of managing the local links to institutions, resources and careers (Rip 1990: 389).[4]

On the research level, the final outcome of research efforts has to be contextualised, written and edited. In these local actions, researchers respond to the emergent science level (in the form of existing and expected body of knowledge) in an anticipatory mode in which the existing claims in the body of knowledge are partially deconstructed and reconstructed, but also accepted to a large extent (Fujigaki 1998). In disciplinary fields, the problems, methods, data and expected results that researchers use in their work are constituted within the field, and one expects that this is reflected in the way researchers refer to the relevant literature.

In dynamic (emerging) fields, with high growth rates, entrance barriers may be low for new researcher to contribute. Often diverging skills, infrastructures and methods are used in these circumstances. At the early stages of development of a new field, under conditions of high uncertainty, researchers may accumulate marginal competencies. Due to the initial distance of researcher's competencies from emerging developments, high opportunities for innovation may lead to an increasing level of differentiation of the knowledge base. However, also in established fields with a strong disciplinary identity a wide variety of (diverging) research practices occur. For example, in genome research information scientists increasingly contribute to the field with a heterogeneous set of tools and search algorithms in addition to the 'traditional' labwork of microbiologists.[5]

In some cases the emergent knowledge base is such that researchers are compelled to explore the same set of cognitive, technological and methodological resources and to adopt the same search procedures. In other cases, the emergent knowledge base instead allows researchers to pursue different behaviours. The possibility to exploit emerging opportunities is determined by the need to co-ordinate due to the mutual dependency and task uncertainty. Infrastructures provide an important example of mutual dependencies between researchers. The importance of infrastructure for the progress of science has been repeatedly emphasized in history and sociology of science (Bonaccorsi 2008). The literature on big science has largely discussed the implications of large infrastructure for the organization of research activity. The obvious examples are accelerators and synchrotrons

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[4] The increasing use of ICTs at the scientizing level feeds into changes in the researching practices of career choices and reputation building, thus giving rise to different dynamics of identity formation for scientific communities. Scientists' visibility does not rely exclusively on the number of publications and their peer citations but can increasingly result from a well-designed and well-linked homepage providing scientific content. The Web and the visibility it provides to a wider audience increasingly become resources strategically managed by scientists in their positioning (Heimeriks and Vasileiadou, 2009).

[5] A group of Chinese scientists has discovered the main biochemical pathways in drug addiction—and without having to do a single (traditional) experiment. There are now so many known biomolecules, and the databases linking them are so good, that it is possible to [digitally] investigate this ´bibliome´ in its own right. 'Going by the book' Jan 10th 2008, The Economist

in physics, observatories in astronomy, white chambers in microelectronics, nuclear reactors in nuclear engineering, wind tunnel and vacuum chambers in aerospace engineering. Knowledge production is often based on a fixed coefficient technology, whereby the output falls to zero if a given piece of equipment is not available. Bonaccorsi points out that this creates strong coordination problems (Bonaccorsi 2008). Since substitution between factors is often unfeasible, coordination failures are likely to occur. Coordination mechanism of expensive infrastructures can be legitimised more easily for stable fields of knowledge production. Therefore, large infrastructural investments are much more likely in stable established fields than in dynamic and emergent fields.

The importance of science has increased in recent years as a result of the emergence of the knowledge society: a society in which theoretical and codified knowledge is an increasingly important resource for social, economical, political and innovative processes (Webster 2006). In a knowledge-based society, most societal problems require new knowledge developments, and thus 'problem-based' R&D will become more and more important and encompassing. In addition more and more social actors (different ones in each field), beyond the usual R&D stakeholders, wish to be involved in such debates. These societal dynamics can be made visible by the distinction between appropriability and scientific entry barriers. For example, the contribution of non-academics may reduce the strength of scientific entry barriers in a field, while the contribution of exclusively academic researchers may decrease the appropriability of knowledge. Scientific and technological advances originating outside academia, represent an important source of knowledge for the innovative processes of researchers (Marsili 1999). Scientific and technological advances increase the general level of scientific opportunity.

The nature of knowledge differs in terms of tacitness, observability, complexity, and systemic nature (Winter 1984). A continuum range can be established between highly tacit to fully articulable knowledge, depending on the ease with which it can be communicated in a codified symbolic form. Thus, the distinction between research and science, also translates into a distinction between codified knowledge (science) and tacit knowledge and organisational routines (research). Furthermore, the relationship between these dimensions becomes increasingly important in socio-economic production processes (Cowan, David et al. 2000).

5. Governance

The complex adaptive system perspective on knowledge dynamics highlighted two categories of insufficiency: insufficiency in the governance devices and insufficiency in the theoretical models currently available to address the former.

The policy models for research governance that we discussed in section three, insufficiently addressed the vertical organisation of knowledge dynamics in terms of the different levels of analysis. Furthermore, the interactions between these dynamics needs to be articulated in order to design appropriate policy interventions. In the previous section, we addressed these mechanisms through which different levels in knowledge dynamics interact through positive and negative feedbacks.

We argue that the notion of a regime is needed that combines the dynamics of a field in research, science and society. In distinction from traditional science policy approaches, this conceptualisation includes the (field specific) interaction of researchers in a given location with the global scientific context and the societal context in which they operate. Governing knowledge production through disaggregated measures means targeting in a distinct way not only different fields, but also, and more importantly, the interactions between local research practices, emergent scientific landscapes, and the field's relationship to its societal context.

The conceptualisation suggested here, also allows us to elaborate on the emergence of regimes. In addition to Bonaccorsi, the notion of regime has been used by Nelson (Nelson 1994) for technology, firms and institutions and by Leydesdorff (2000) for the triple helix of science, government and company interactions. All these studies stress the emergence of stable patterns from co-evolutionary processes. More precisely, three sub-dynamics can generate a stable regime if these dynamics are compatible with each other. Recombinations of three sub-dynamics generate various types of complex behaviour and can generate stable regimes by lock-ins between two of the sources if the third context is stable and compatible with the others (Dolfsma and Leydesdorff 2009). This observation is consistent with Kauffman's NK-model (Kauffman 1993).

Given the diversity of search regimes that evolve from interactions between researching environments, disciplinary identities and the increasing interactions with society, the 'one size fits all' answer is becoming increasingly obsolete. Policy-makers can not apply the same framework and instruments to different search regimes. Policy instruments are not effective because of their intrinsic properties, but because of the specific context in which they are applied. Policies that ignore the specific characteristics, dynamics and requirements of different regimes across fields may be ineffective or even harmful. It is necessary to understand the networked nature of the research dynamics in each field, its geographical distribution and the types of organizations that are involved.

An important consequence of science as a complex adaptive system with path dependency occurring at multiple levels, is that there is no precise way of determining the most effective scale and scope for public intervention (Laranja, Uyarra et al. 2010). More generally, this means that we should accept different relevant spaces for public intervention, since some regimes require international research policies while others are the realm of regional policies. This means that the location of new research programmes and the geography of scientific knowledge production more broadly, is subject to path-dependent dynamics where research programmes may prosper in some locations and to become marginalized in other locations (Arthur 1994). There is a tendency across countries and regions to apply the same ideas in an unimaginative way, instead of trying to find original areas of expertise (Foray 2006). Not all regions will be able to succeed in becoming world renowned high-tech centres of excellence. A vision is needed to know where the region wants to go within the knowledge economy, to create unique locational advantages in relation to the global body of knowledge and the societal dynamics.

6. Discussion and conclusion

We started this paper with the observation that research governance is a complex matter. We argued that the notion of complex adaptive systems help to shift our perspectives from mechanic and deterministic assumptions on science and innovation governance to a more dynamic way of thinking. Complex adaptive systems bridge local, global and contextual dimensions thus enabling us to better understand how researchers affect and depend on each other, the scientific community and society.

The major developments in research and innovation that we addressed make more informed and specific policy interventions necessary. The first development relates to the changing dynamics of knowledge production. The second development is related to the globalisation of the sciences and the paradox that scientific knowledge is considered to be universally accessible, while funded on a local and national basis(Wagner 2008). The third challenge concerns the changing interface of science and society with the rise of the information society or knowledge economy. On different levels of analysis the challenges all point at increased heterogeneity and complexity.

The debate around these challenges in the last decades gave rise to concepts such as Mode 2, which attempts to capture sides of this increased heterogeneity and complexity. However, when we adopt the idea of field-specific regimes that co-evolve from the changes in research, science and society, a “one size fits all” resolution would hinder the dynamics of interactions among its levels. So rather than constructing a simplified stereotype of knowledge production (such as Mode 2), it seems more useful to embrace the heterogeneity and complexity emerging in knowledge production.

This conceptualization proposed here allows us to disaggregate knowledge dynamics both in horizontal (field related) and vertical (level related) dimensions by articulating the three different dynamics and their path dependencies (in research, science and society) in co-evolution with each other to produce distinct search regimes in each field. For research governance this implies that while generic measures can sometimes be helpful, there is clear need for disaggregated measures. The success of research policy initiatives and instruments depend not just on the way they address an issue, but also on how they match the existing path dependencies on the level of research, science and society. Their strength, as well as their successes, have to be evaluated in this way, as a multi-level (and multi-actor) approach to evaluation. The multi-level approach is additionally important because concrete actions and interactions add up to effects at more levels (Simon 1973). Research governance thus entails a linking and sinking strategy as proposed by Wagner (2008). It links to global science dynamics and locally ‘sinks; efforts by taking into account local research dynamics with respect to stakeholders, infrastructures and the local knowledge base in terms of human resources and skills. Governing knowledge production through disaggregated measures means targeting in a distinct way not only different fields, but also, and more importantly, the interactions between local research practices, emergent scientific landscapes, and the field’s relationship to its societal context. If all three “levels” are aligned, there is a stable regime.

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